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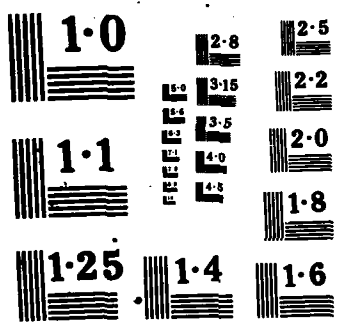

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A HELICOPTER FLIGHT EVALUATION OF KINESTHETIC-TACTUAL DISPLAYS: AN INTERIM REPORT

Alan M. Poston
Richard S. Dunn

March 1986

U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

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The kinesthetic-tactual (KT) display concept employs moveable elements incorporated in a pilot's flight control handgrips. A series of laboratory and simulator studies conducted since 1976 has shown that this touch-based display approach can substitute for visual displays or augment them in useful ways. This report describes the first helicopter flight evaluation and demonstration of KT displays. Flight performance data were collected to compare the conventional visual display condition to KT conditions. Performance results as

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well as pilot opinion comments are discussed along with conclusions and implications for further KT system development. This is an interim report because in-depth analysis of the flight data is still underway.

See p.

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CONTENTS

A HELICOPTER FLIGHT EVALUATION OF KINESTHETIC-TACTUAL DISPLAYS: AN INTERIM REPORT

INTRODUCTION

Tactual display devices have been tested in many forms as potential replacements for visual displays. The kinesthetic-tactual (KT) display has been investigated in Army-sponsored laboratory and flight simulation studies since 1976. This display employs a motor-driven moveable element in the pilot's control grip to transfer flight control information. In use, a single-channel display is incorporated in the collective control handgrip; a two-channel device replaces the cyclic stick handgrip.

In contrast to most other tactual display concepts, research on the KT devices indicates that they can duplicate the functions of visual displays for compensatory and pursuit manual-tracking tasks up to frequencies slightly above one cycle per second. This includes most of the manual control tracking tasks encountered in helicopter mission applications, both in navigation or obstacle avoidance tasks, and in many attitude control tasks. The most promising potential benefits in mission applications of KT displays are for conditions where visual task demands are high; for example, helicopter terrain flight requiring continuous visual attention outside the cockpit, and where use of conventional visual displays is complicated by night vision devices.

Some research favors the hypothesis that touch sense modality-specific faculties can be brought to bear on the sensory task demands in some applications (Burke, Gilson, & Jagacinski, 1980). If this is so, use of KT displays may do more than redistribute the information transfer task demands among fixed resources; it may increase the total information transfer capacity by expanding the available resources. Thus, KT displays may provide reduced pilot visual workload or increase information transfer to the pilot.

Expected benefits from KT applications may also include task performance improvements associated with high control/display compatibility. It is also reasonable to expect that when KT displays are employed as redundant sources of information along with the conventional visual displays, some reduction in the risk associated with mission tasks may be achieved. Thus, potential KT display benefits may include workload redistribution to more readily available sensory faculties, workload reduction due to increased sensory capacity, performance enhancements from increased control display compatibility, and reductions in mission task risks.

Research to date on the KT display concept has developed a methodology for comparison of visual and KT displays centered on the critical tracking task methodology (Burke, Gilson, & Jagacinski, 1980 and Jex, McDonnell, & Phatak, 1966). The method was employed to refine the mechanical and electronic design of the KT displays and to establish the basic control law requirements.

To improve performance, tactual displays require control law features to enhance small signals in order to overcome tactual threshold effects. Display "quickening" is also required in some applications and is obtained by adding higher order terms. A signal proportional to the error or command is generated and is mixed usually with its first derivative (rate aiding) to "quicken" the display movement. Further laboratory research obtained display-operator transfer functions to establish the speed and accuracy of information transfer expressed in terms of frequency and phase lags (Jagacinski, Flach, & Gilson, 1983). It is from these data that KT suitability to many flight tasks can be predicted. Trials and demonstration work in flight simulations indicated that KT displays are feasible for in-flight application and that operator workload and pilot acceptance effects would both be favorable (Gilson, Dunn, & Sun, 1977).

This report describes the first actual in-flight test and demonstration of KT displays in helicopter applications. It describes the KT display system, including its digital computer controller, the test aircraft, the in-flight system control law development process, and a series of four investigations comparing flight performance and workload for several simple in-flight tracking tasks guided by visual displays, KT displays, or both.

OBJECTIVES

The purpose of this flight investigation was to serve as a pilot study to determine the usefulness of a KT display system in improving pilot performance and reducing workload. Should positive results be found, a more in-depth follow-on investigation may be warranted.

The specific objectives were to:

1. Determine the compatibility and identify any integration problems of installing the KT display system in a helicopter.

2. Determine if incorporating the KT system improves pilot performance or allows equal performance with a reduction of required visual instrument information.

TEST SYSTEM

Specialized apparatus employed in this flight assessment included a flightworthy prototype KT display and controller system, an instrumented Army UH-1H helicopter, and a secondary task control/display and recording system termed the workload assessment device (WAD). All involve digital electronics and are described briefly here.

A flightworthy KT display system was constructed by System Research Laboratories under a Navy contract. The system includes both single- and dual-channel prototype KT displays similar to the illustrations in Figures 1 and 2. The system consists of two tactual feedback effectors; one on the collective control and the other on the cyclic control. The KT system

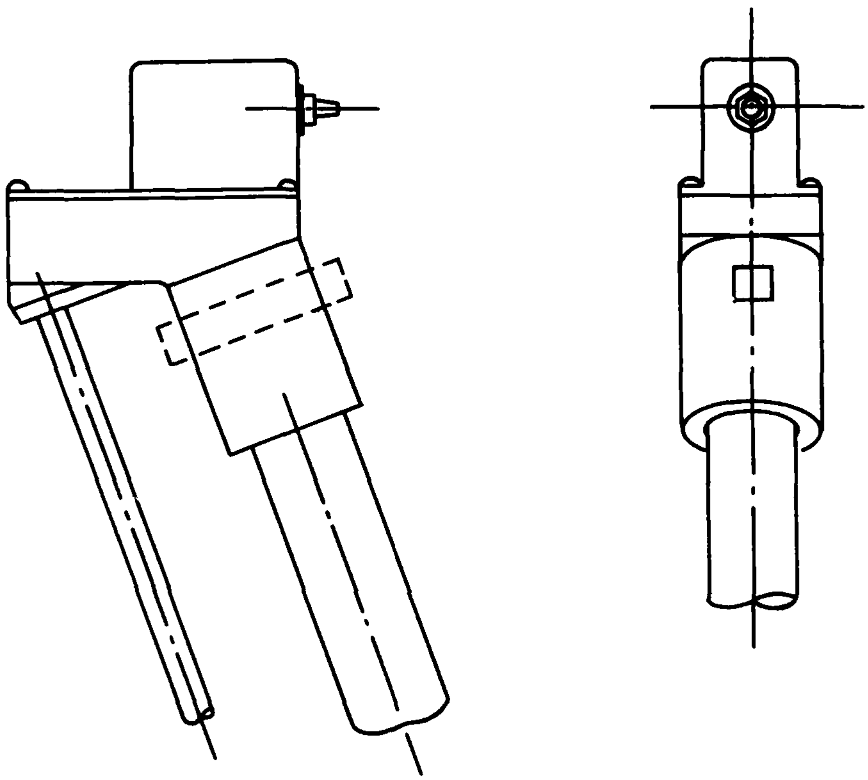

Figure 1. Single-channel KT display.

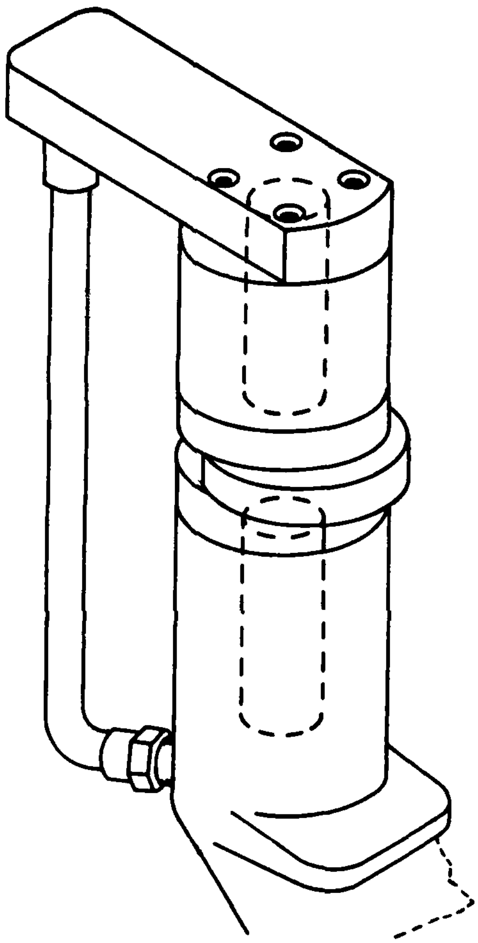

Figure 2. Dual-channel KT display.

monitors the helicopter's flight parameters and provides the necessary control signals to each effector for the pilot to feel. The effectors protrude in the direction the control is to be moved, as shown in the example of Figure 3, and the magnitude of the protrusion is proportional to the required control displacement to correct the error. Because the KT system does not have any effectors on the yaw pedals, corrections for heading were included in the cyclic control.

The controller for the KT display was developed using a National Semiconductor Corporation (NSC) CIMBUS system containing standard NSC-assembled boards and a prototype wirewrap board for KT interface circuitry. The controller employed a CIM-802 CPU board with an NSC 800 microprocessor, a CIM-201 serial input-output board, a CIM-108 RAM/PROM memory expansion board, and a CIM-411 analog input board. The computer employs P2CMOS components enabling it to be powered by an internal rechargeable battery. The KT interface card captures parallel datum from the aircraft pulse code modulation encoder and provides status as to when the datum is valid. This datum is interpreted in software; and, in turn, a software command sends an 8-bit piece of parallel datum. This datum represents a location, one of 256 possible, to be relayed to one axis of the KT display. There are three analog devices, AD7524LN digital-to-analog (D/A) converters, one for each axis of the system. The output provides a linear voltage to the respective display motor. The voltage is proportional to the distance which the display has to travel. The system utilizes principles of autocontrol in that it allows feedback from the synchro to assist in positioning the motor, without software intervention.

The terminal communications device used by the in-flight experimenter to operate the software in the KT controller was a GR Electronics pocket video display unit (VDU). It has a 2 x 20 liquid crystal display and is self-powered. The KT software and controller design permitted sampling and computation allowing the KT displays to be updated four times per second.

The WAD, SRL Model WAD8085, was employed to provide a secondary task as a workload measurement technique. It has been described fully in Schiflett, 1980. Briefly, it presents a series of 39 single letters on an easily visible liquid crystal display. Pilot responses, from two Brady XYMOX membrane switches on the collective, indicate whether each letter is or is not one of a previously memorized set. Reaction time and accuracy are recorded for each response. The WAD was controlled by the in-flight experimenter by a TERMAFLEX HT/2 terminal.

A UH-1H helicopter, S/N 72-16302, assigned to Phillips Army Airfield, Aberdeen Proving Ground, MD, was used as the flight vehicle during the investigation. The UH-1H is equipped with a Helicopter In-Flight Validation System (HELIVALS) (Frezell, Herald, Camden, & Fry, 1980) which provides a dynamic operational measurement tool to gather and validate in-flight performance of aircrew members.

The HELIVALS measures, in real time, flight control displacements, pitch, roll, rate-of-turn, aircraft accelerations, aircraft velocities, radar and barometric altitude, heading, airspeed, and geographic position in universal transverse mercator (UTM) coordinates.

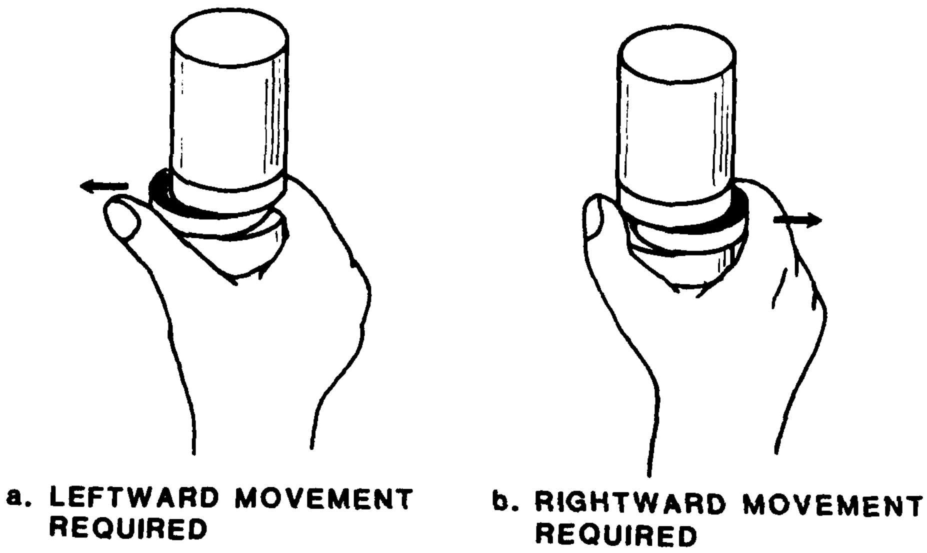

Figure 3. Dual-channel KT display operation.

For these tests, the HELIVALS digitized and recorded altitude, airspeed, and heading data, along with several other parameters. The digitized data were employed by the KT controller software to generate error signals representing direction and magnitude of errors from the desired conditions for each variable--altitude, airspeed, or heading. The software was limited in the complexity of information transformations that it could make. It could not compute stick position commands to return to a desired condition; for example, as in a flight director. Errors could not be computed to permit guided maneuvers such as turns or descents. This limited the information displayed to pure error information for steady tracking tasks. The experimenter, via the pocket VDU, could control the gain or sensitivity of the KT display; and between trials, the nominal value from which errors were computed could be set.

INITIAL FLIGHT TESTS

After modifications to the test aircraft to install the KT and WAD systems, the first phase of the effort was conducted. All flight testing was conducted in visual flight rules (VFR) weather using the Navy project pilot as research pilot and the Army project pilot as safety pilot. The first ground and flight operations were tests to establish the display control law software and to confirm that the displays, the system controls, and the WAD display and response devices were all working properly and could be operated in flight. Final values for the linearly-scaled display sensitivities were established. The collective KT display provided five-eighths of an inch of total extension in either direction. Full-scale deflection of the collective KT display was programmed for errors of 50 feet above or below the nominal target altitude in forward flight. For hovering tasks (using radar altimeter inputs), selected sensitivity was full-scale deflection for errors of 10 feet. Airspeed errors were displayed by fore and aft movements of the cyclic KT display disk with 5-knot errors causing full-scale deflection of nine-sixteenths of an inch. Heading errors were displayed by left and right deflection of the KT cyclic display. Full-scale deflection was displayed both in forward flight and in hover tasks by 5-degree errors. All displays were functional and usable over a large range of gain settings; for example, any sensitivity between ± 3 knots and ± 10 knots was found to be effective for tracking airspeed. Under gusty conditions, the lower sensitivity (± 10 knots full scale) provided better tracking performance. The nominal values selected represented, in the research pilot's opinion, a single gain value most useful over all flight conditions encountered.

At the end of 13 flights, requiring 16.6 flight hours, all systems were performing as desired. The research pilot had demonstrated tracking in forward flight tasks and two hover tasks. The forward flight tasks were tracking a selected airspeed, a selected altitude, and a selected heading. These tasks were performed separately and in combinations. The hover tasks included holding a radar altitude and holding both altitude and heading.

Results indicated that the pilot could perform the selected tracking tasks by reference to the instrument panel displays with KT system off, or by reference only to the KT displays with the instruments covered. This phase also demonstrated that the various tracking tasks could be performed while the secondary task provided by the WAD system was performed. For this evaluation, the WAD presented 39 letters in each trial series at an average interstimulus interval of 15 seconds (varying between 10 and 25 seconds). Stimulus letters were displayed on a liquid crystal display device mounted to the left of the instrument panel. Memory set sizes had one, two, or four letters and were memorized by the pilot prior to each test series.

At the conclusion of the initial flight test series, the research pilot, who had essentially "calibrated" the system for himself and had demonstrated all KT-guided tracking tasks, changed roles with the safety pilot. The safety pilot, without prior KT display flight experience, performed two flights to obtain an independent assessment of the system's sensitivity settings and to demonstrate skill acquisition in learning to use the KT displays for the various tracking tasks. A trials-to-criterion procedure was established using a software routine held in the KT controller. Maximum permissible tracking errors representing 100-foot altitude, 10-knot airspeed, and 10-degree heading were established. For each tracking task, sequential 30-second trials were scored as the KT controller monitored error size. The experimenters established that 10 sequential trials without exceeding the error values would be taken as an indication of acceptable initial skill level in using the KT displays. For calm air conditions, this procedure appeared to be successful. On the third try, the new evaluation pilot reached criterion-level performance in all tracking tasks both with and without the WAD-based secondary task in operation. He agreed that the selected KT sensitivity settings were acceptable.

FLIGHT INVESTIGATIONS

The second phase of the effort included four flight investigations. Three investigations developed performance and workload comparisons for all combinations of the forward flight tasks; one investigation provided comparisons for the two hover tasks. Two Navy test pilots and two Army operational pilots served as test subjects. All were qualified in the UH-1. Each subject served in all conditions. All subjects wore standard flight clothing, including flight gloves.

Ground training, using a training software routine, was provided in two sessions of about 1 hour each. Training included KT display operation and WAD-based secondary task operation. For each investigation subjects were provided a 1-hour familiarization flight to sample all investigatory tasks and to practice both KT display use and secondary task performance. Each investigation was preceded by KT display practice using the trials-to-criterion scoring procedure until the subject completed 10 sequential trials of 30 seconds each without exceeding the stated error criteria applied to the tasks involved. In addition, trial initiation also

depended upon agreement by both the test subject and the safety pilot that the subject was ready for data collection trials.

Investigation I involved airspeed tracking at 80 knots nominal. Display conditions were use of the airspeed indicator, use of the KT display with the airspeed indicator covered, and a combination condition in which the KT display and airspeed indicator were available. Separate tracking task trials were conducted for each WAD memory set size (one, two, and four letters) using the WAD-based secondary task. The order of presentation for each WAD memory set size as well as KT and visual presentation order was counterbalanced, and the combined display condition was always last. Trial length was 6 minutes.

Investigation II did not employ the secondary task. It provided direct flight performance comparison data on visual, KT, and combined display conditions while tracking altitude, heading, and simultaneously tracking altitude and airspeed. The general procedures were the same as for Investigation I; KT and visual presentation order were counterbalanced followed by the combined display condition. Trial length was 10 minutes.

Investigation III required simultaneous tracking of altitude, heading, and airspeed and included the secondary task. The procedure was identical to Investigation I.

Investigation IV required tracking altitude and both altitude and heading in a hover. Secondary task data were collected for simultaneous altitude and heading tracking only. Trial lengths were 10 minutes and 6 minutes respectively. The altitude used a hover position over a closed runway to ensure stable operation of the radar altimeter data source.

RESULTS AND DISCUSSION

Data collected included extensive in-flight comments, post-flight written debriefing comments, flight performance, and secondary task response speed and accuracy. Difficulties in reading, filtering, and using the flight performance records have been encountered. This has delayed detailed analysis of the flight performance results. At this writing, only summary descriptive statistics have been computed for inspection.

For each trial, the available data include mean tracking performance, the standard deviation of that distribution, and the range of extreme values. The mean values were close to the nominal values the subject was tracking (i.e., 80 knots airspeed, 1,500 foot altitude, and 315° heading), so little would be gained by comparing means. There was a small difference between the means of the KT and visual conditions due to display errors within the instruments. This difference was corrected for in the analysis. Extreme range measures are not a reliable inspection aid since they represent only two values and may not be representative of the distribution pattern. Hence, a direct comparison of the standard deviations (dispersion measures) was the only viable comparison to be made from the available

data. For mean values which were essentially the same, it follows that the higher tracking performance quality will result in a smaller dispersion.

For Investigation I, inspection of the dispersion measures showed no visible effect due to WAD memory set size. Performance of the test subjects compared to one another did not show consistent superiority of any individual. The results indicate a small but consistent advantage for the visual display (airspeed indicator), followed in order by the combined and then the KT display condition. Summary values for all conditions and subjects are shown in Table 1 which combines the results from 24 trials. A final conclusion will have to await more suitable analysis of the data.

Investigation II summary values are shown in Table 2. Altitude variations for the KT display in the simultaneous altitude and airspeed tracking task appear to differ widely at levels which may be of operational importance. Each summary value represents the results of eight trials, 10 minutes in length.

Investigation III summary values are shown in Table 3 for 24 trials of 6 minutes each.

Investigation IV summary values are shown in Table 4 for four trials of 10 minutes each for altitude tracking and 12 trials of 6 minutes each for altitude and heading tracking.

For all investigations, a detailed inspection of the individual trials indicates that atmospheric flight conditions are the main determinant in flight task performance results. Every attempt was made to compare data on the same flights and near in time to minimize atmospheric conditions effects. Practical flight test scheduling considerations often prevented this. Normal changes in altitude or heading between trials sometimes resulted in differences in atmospheric effects sufficient to dominate the test findings. Atmospheric turbulence is an uncontrolled and important variable in all of these investigations.

Because gust effects so strongly predominated in determining the quality of tracking performance, the trials-to-criterion procedure did not produce meaningful records. It did aid, however, in supporting the decision that each test subject had sufficient in-flight training to begin performance testing.

Assessment of secondary task performance data has not been completed. Data are not presented because significance testing is positively required for interpretation.

Review of the subject's verbal and written comments indicated a high degree of pilot acceptance with regard to the KT display concept and included numerous suggestions for KT system improvements and future applications. All subjects indicated a desire to use the system for more complex tracking tasks.

Extensive pilot and experimenter comments were recorded during these flights. They clearly show that the test equipment had numerous annoying

TABLE 1

Results of Investigation I

Information Condition	Mean	Standard Deviation	Range
Maintain Airspeed (knots)			
Instruments	75.05	1.44	8.55
KT Display	73.87	2.28	13.12
Combination	74.74	1.84	10.81

TABLE 2

Results of Investigation II

Information Condition	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
Maintain Altitude (feet)						
Instruments	866.75	19.82	196.20			
KT Display	883.00	20.72	117.41			
Combination	883.25	17.15	103.85			
Maintain Heading (degrees)						
Instruments	-	1.04	11.18			
KT Display	-	1.91	17.69			
Combination	-	2.75	22.95			
Maintain Altitude (feet) and Airspeed (knots)						
		Altitude			Airspeed	
Instruments	908.50	16.93	92.04	74.85	1.79	10.14
KT Display	891.00	36.38	188.80	74.68	2.33	13.11
Combination	885.50	27.99	174.05	74.37	1.77	13.66

NOTE: A mean value is not shown for heading because of the different nominal headings used.

TABLE 3

Results of Investigation III

Information Condition	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
Maintain Altitude (feet) and Airspeed (knots)						
		Altitude			Airspeed	
Instruments	869.79	25.01	130.00	75.13	1.80	10.00
KT Display	893.12	27.32	134.72	74.42	2.08	11.13
Combination	880.09	27.90	139.68	74.13	1.80	9.56

TABLE 4

Results of Investigation IV

Information Condition	Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
Maintain Radar Altitude (feet)						
Instruments	65.09	2.88	20.12			
KT Display	65.33	3.48	21.98			
Combination	64.95	2.45	16.39			
Maintain Radar Altitude (feet) and Heading (degrees)						
		Radar Altitude			Heading	
Instruments	65.94	3.48	25.64	178.59	3.06	23.59
KT Display	65.90	3.48	19.43	181.00	3.31	25.85
Combination	66.27	4.00	21.44	181.56	4.36	30.87

deficiencies; for example, the KT display drive motors did not have high enough torque and could be inadvertently held in one position by a pilot's finger pressure. Use of the display devices required the development of new habits to ensure both a light touch and attention to the display device. Also, the WAD apparatus was often difficult to see due to glare and display location. The switches, located for left thumb operation, detracted from easy use of the collective KT display device.

The comments and the flight performance results also showed, however, that the KT devices were functional in flight and that tracking task performance similar to visually-guided tracking could be obtained for all of the tested conditions and tasks. Overall, the pilot's comments were highly favorable toward the potential for a KT display concept. The most favorable comment was toward the hover altitude tracking task, saying that altitude deviations of 1 foot were easily detected and corrected.

Results of the test also clearly indicated that both visual and KT display system tracking are adversely affected by gusty or turbulent flight conditions. Gusty conditions quickly diminished the precision of tracking performance and had a more adverse affect on the KT display based tracking tasks. To accommodate this, any operational system will need to have adaptive or adjustable gain settings or other control law elaborations beyond the limits of the software employed by this test system. It should be noted that the tracking tasks developed for this effort were selected to fit the constraints of the software and the installed aircraft sensors. No relationship between these particular tasks and any practical mission-related tasks is necessarily present.

CONCLUSIONS

Kinesthetic-tactical displays have been successfully demonstrated in simple tracking tasks in helicopter flight operations. A KT display can be integrated into a helicopter with only minor modifications to the aircraft. Failure of the KT display system will in no way affect the helicopter's flight controls. Basic in-flight operability of the display concept predicted by laboratory and simulator studies has been confirmed. The simple controller software used in this investigation to display error information using static gains and linear scaling is not likely to be adequate for practical flight task applications in its present form. Conclusions with regard to workload effects and other experimental outcomes of interest require further analysis of the data.

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7 — 86